Is Solid State the Future of Lighting?

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Outline

- **Review of history of innovation in lighting**
  - Solid state is not the first “new” lighting technology
  - History is a great teacher of the wrong things to do
- **Conventional technology and the current market**
  - Where are we now
  - The other guy’s aren’t standing still
- **Near term targets of opportunity**
- **Key technology steps**

Some History

- **Technology assaults on the lighting market are not new**
  - Edison's incandescent (c. 1900)
  - Fluorescent (c. 1930)
  - HID (c. 1960)
  - CMH (c. 1995)

Image provide by USDOI

- **Net present value of total investment is huge**
  - 100 years of manpower and capital
  - Key focus has been manufacturing technologies
    - Focal point of automation processes even before electronics
    - No-touch
    - How else does an incandescent lamp cost <7.5¢ to make?

Metrics of The (Ever) Better Light Source

Cost

- First cost
- Operating cost
- Life cycle cost

…inclusive of

- Efficiency
- Socket compatibility
- Fixture integrability
- Maintenance
- Lifetime

Performance

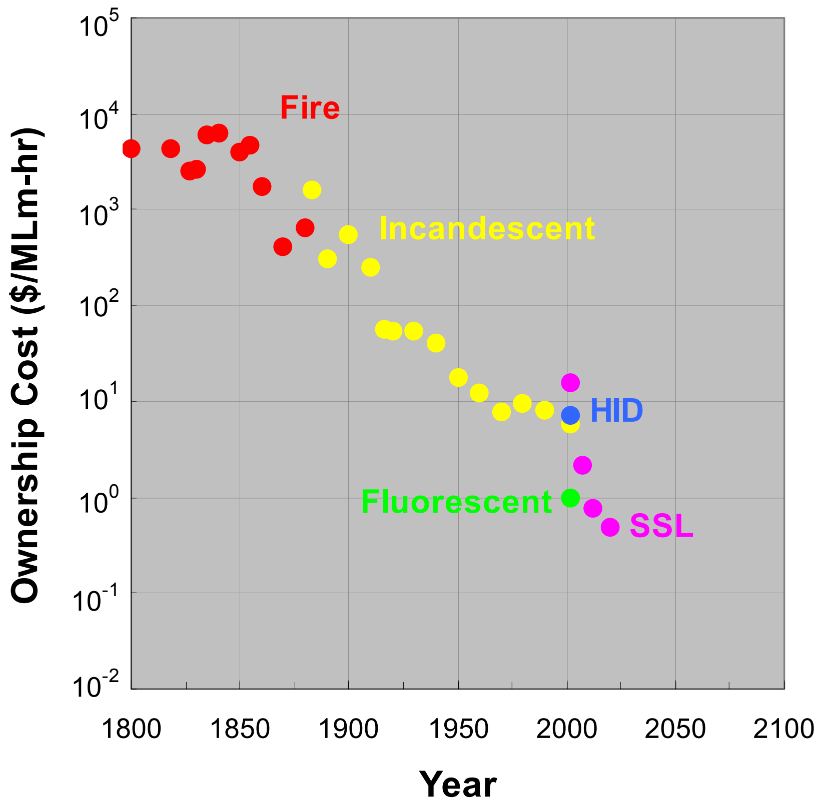
- Color
- Color quality
- Output
- Output intensity
- Optical extent
- Turn-on time
- Re-strike time
- Operating environment
  - Capabilities
  - Characteristics

Performance and Cost are Drivers

- **Performance and cost determine**
  - Which market segments a technology will penetrate
  - How fast and how far
- **Performance characteristics**
  - "Necessary but not sufficient"
  - Gating function on participation in a given segment
- **Cost characteristics**
  - Determine competitive position
  - Drive rate and depth of segment penetration
- **Different market segments apply very different weightings**

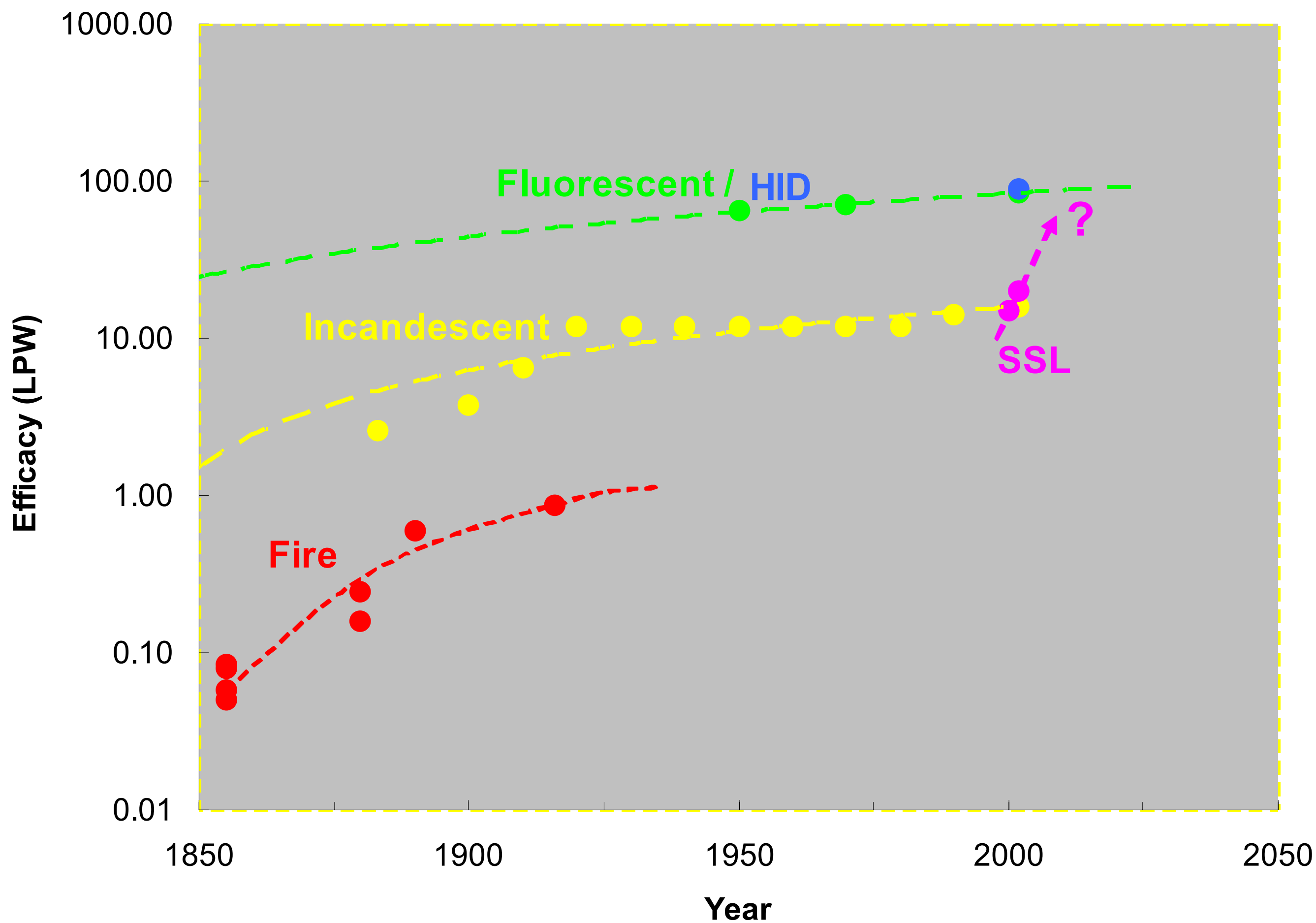
Total Cost of Ownership

- Nordhaus' observation
  - 10x drop in cost per 50 years
- Decrease is:
  - ¾: increase in luminous efficacy
  - ¼: decrease in cost of fuel
- Rollover in TCO for incandescent lamps presaged large shift to fluorescent lamps.
- Fluorescent lamps had substantial presence for 20y prior.



Data for Fire and Incandescence modified from W.D. Nordhaus, in T.F. Breshnahan and R.J. Gordon, Eds., The Economics of New Goods (U of Chicago Press, 1997) pp. 29-70.
Data for SSL-LEDs taken from 2002 U.S. SSL Roadmap.

History of Light Source Efficacy



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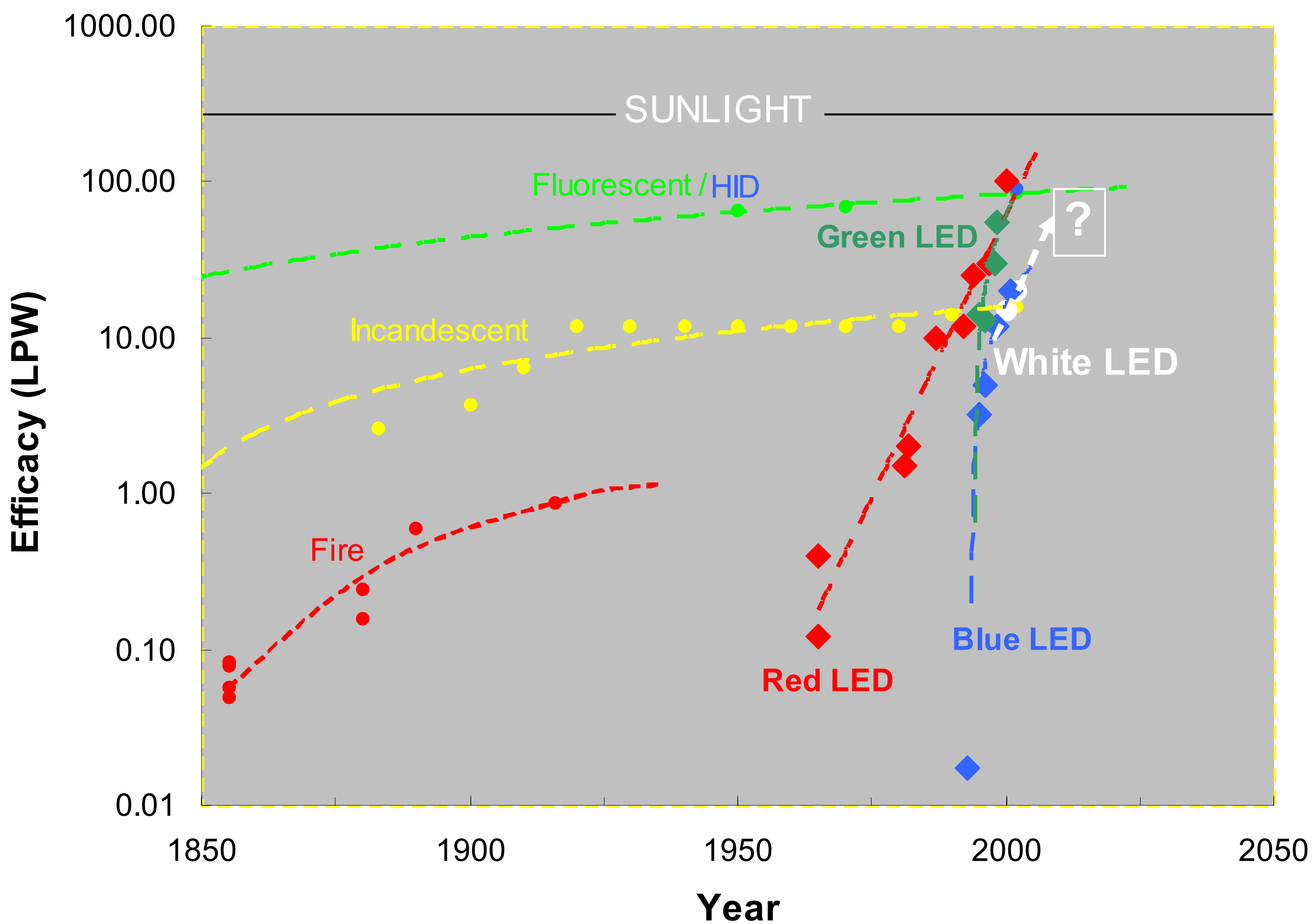
SSL-LED Roadmap 2002

Rapidly Improving LED Performance



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Bergh, A//Craford, M.G.//Duggal, A.//Haitz, R. Physics Today 54, 42-47 (DEC 2001)

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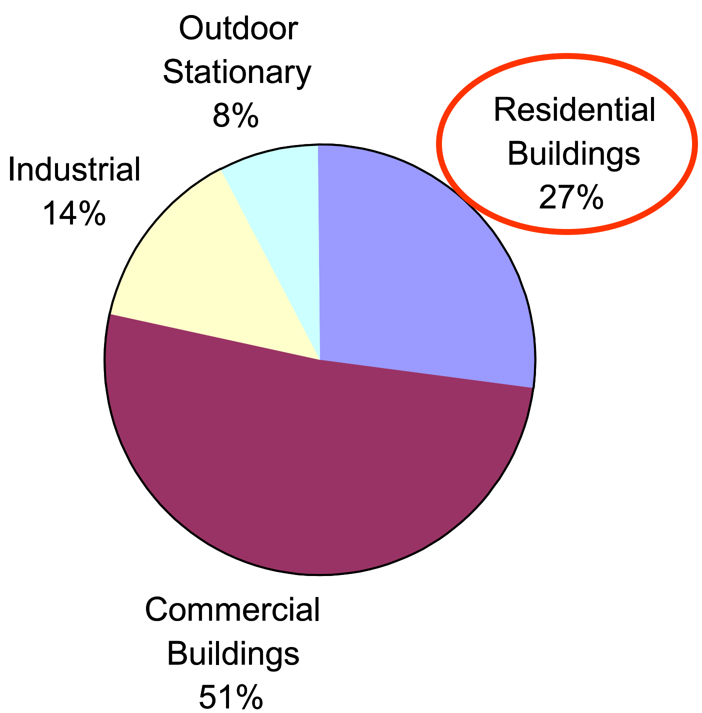
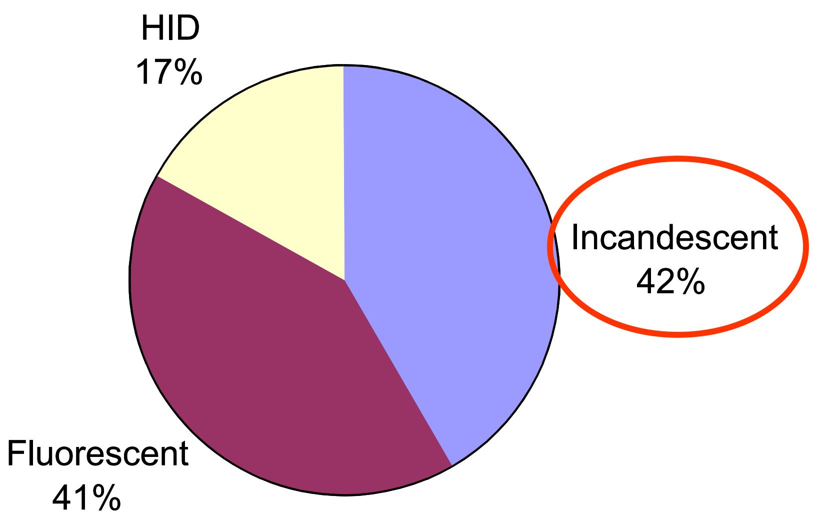
Yet Incandescents Retain Significant Market Share

TOTAL ENERGY CONSUMPTION FOR LIGHTING (2001)

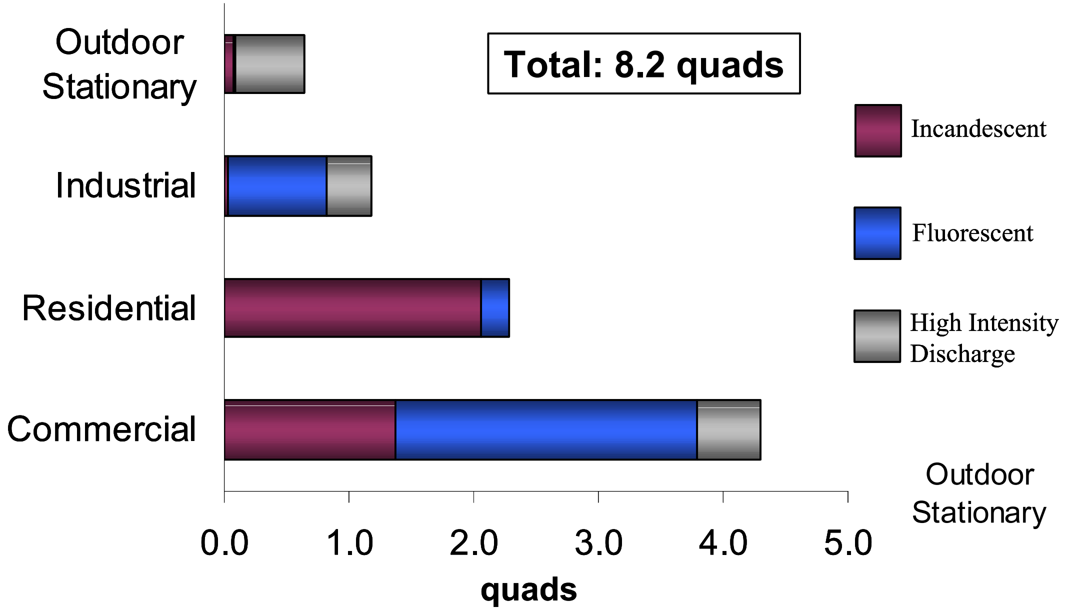
By Building Sector

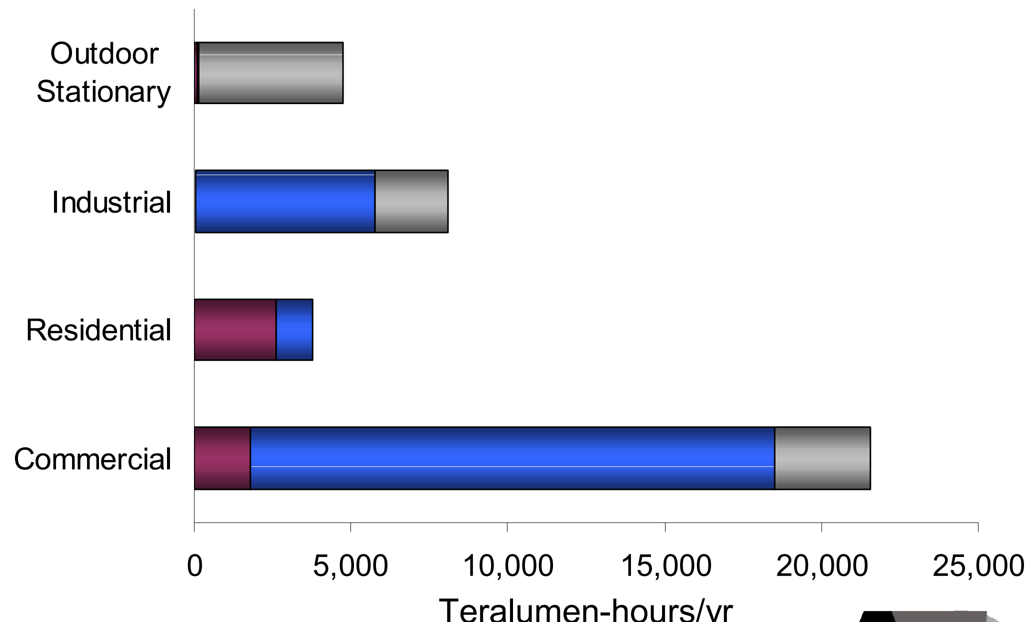


By Light Source



Incandescent Lamps Account for More Energy Use than Any Other Type





Whence CFLs?

<u>Nationwide home improvement store example:</u>

- **13 sales fronts for light bulbs**
  - 8.5 sales fronts for incandescents
  - 4 sales fronts for fluorescents
  - 0.5 sales fronts for CFLs
- **Of the 8.5 sales fronts for incandescent lamps**
  - 3.5 fronts of candle-look-alike incandescents (no CFL alternative)
  - 3 fronts of beam-formed incandescents (no CFL alternative)
    - $5-10/kilolumen
    - 2000 hr lifetime
    - Delivered efficacies max 15 LPW
  - 2 fronts of standard A-line incandescents
    - 24¢ vs. $5 for CFL
    - 1000 hrs life vs. 7000 hrs life for CFL

Total Cost of Ownership favors CFL if Energy Cost > 1¢/kW-hr

…yet CFLs still have only minimal impact on energy use – WHY?

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The Importance of Color and Color Quality

- **Color**
  - Correlated Color Temperature (CCT)
  - Incandescent ~3100K
    - ~same as "warm white" fluorescent
    - CCT(CFL) $\cong$ CCT(incandescent)
  - Daylight ~5000-7000K (D_{65})
- **Color quality: Color Rendering Index (CRI)**
  - Measure the spectral power at several discrete wavelengths
    - Ra(8) uses eight wavelengths (de facto standard)
    - Ra(14) uses fourteen wavelengths (seldom used)
    - Compare to spectral power of equivalent ideal grey body
  - Incandescent lamps feature CRI=100 by definition
  - CRI(CFL) ~ 80
  - CRI differences of 10 or more are observable

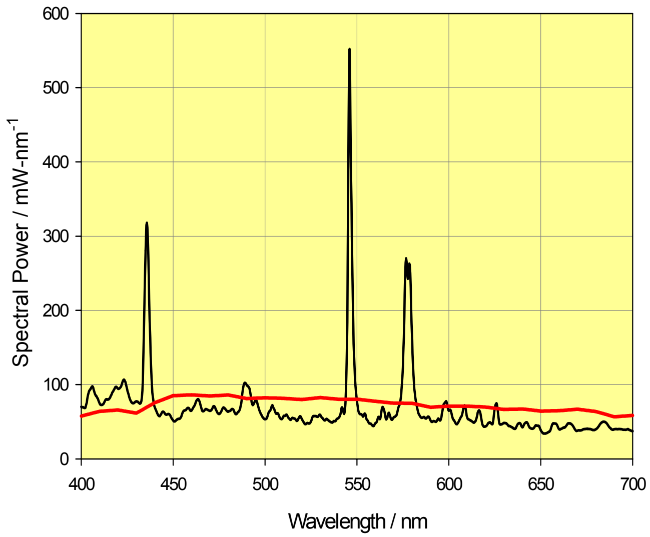
“Gaming” CRI

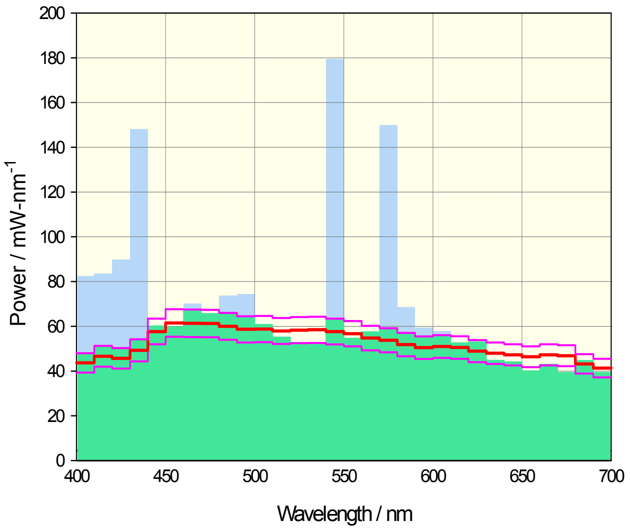
- **Eight wavelength measurement rooted in antiquity**
  - Predates calculators (and computers)
  - Eased calculation burden
  - Eased measurement burden
- **Wavelengths for spectral power measurement fixed by standard**
- **Sparse evaluation of spectral power density distribution function drives “gaming”**
  - Phosphor performances optimized to Ra(8) standards
  - HID fill chemistries optimized to Ra(8) standards

Evolving Color Metrics

- **Computational limitations for evaluating light source color quality are no longer relevant**
- **Alternative measure: % deviation from daylight**
  - Measured output spectrum aggregated into 10nm bins
  - CCT used to compute CIE equivalent daylight spectrum
  - Find ±% displacement necessary to form envelope that contains all of the binned output levels of the light source
    - 420-650 nm
    - Three peak bins allowed to exceed upper envelope
    - Null-light bins not allowed
  - % displacement necessary denoted by mm%Dxx
    - 10%D65 contains all bin levels within ±10% of the CIE D65 spectrum, with maximum three peaks that exceed the +10% envelope.

High Efficiency and High Color

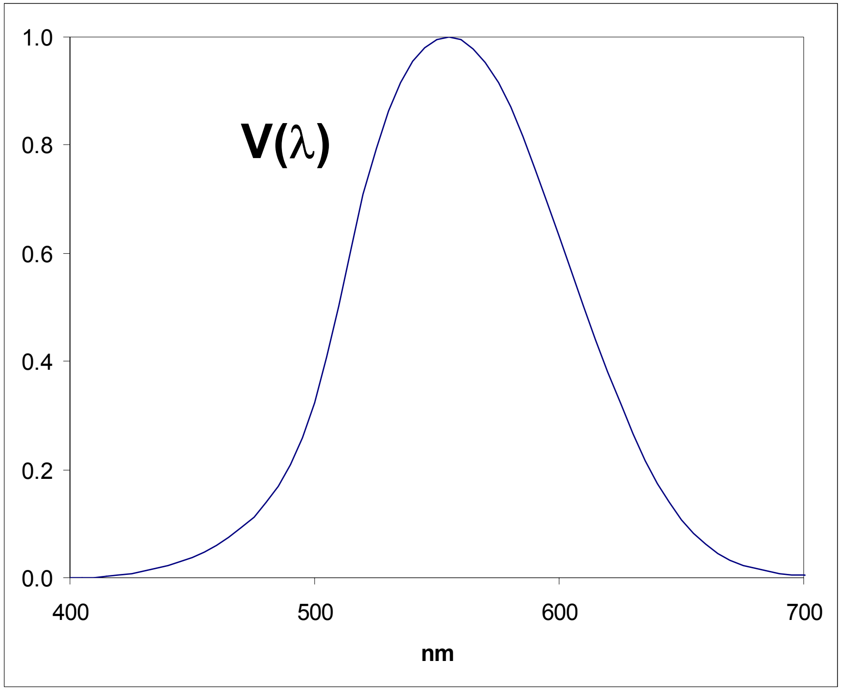




- Compact HID lamp currently in development in DARPA HEDLight program.
- Current efficacy exceeds CFLs (>60 LPW)
- High brightness
- High efficiency optical coupling to fibers or beam-forming optics

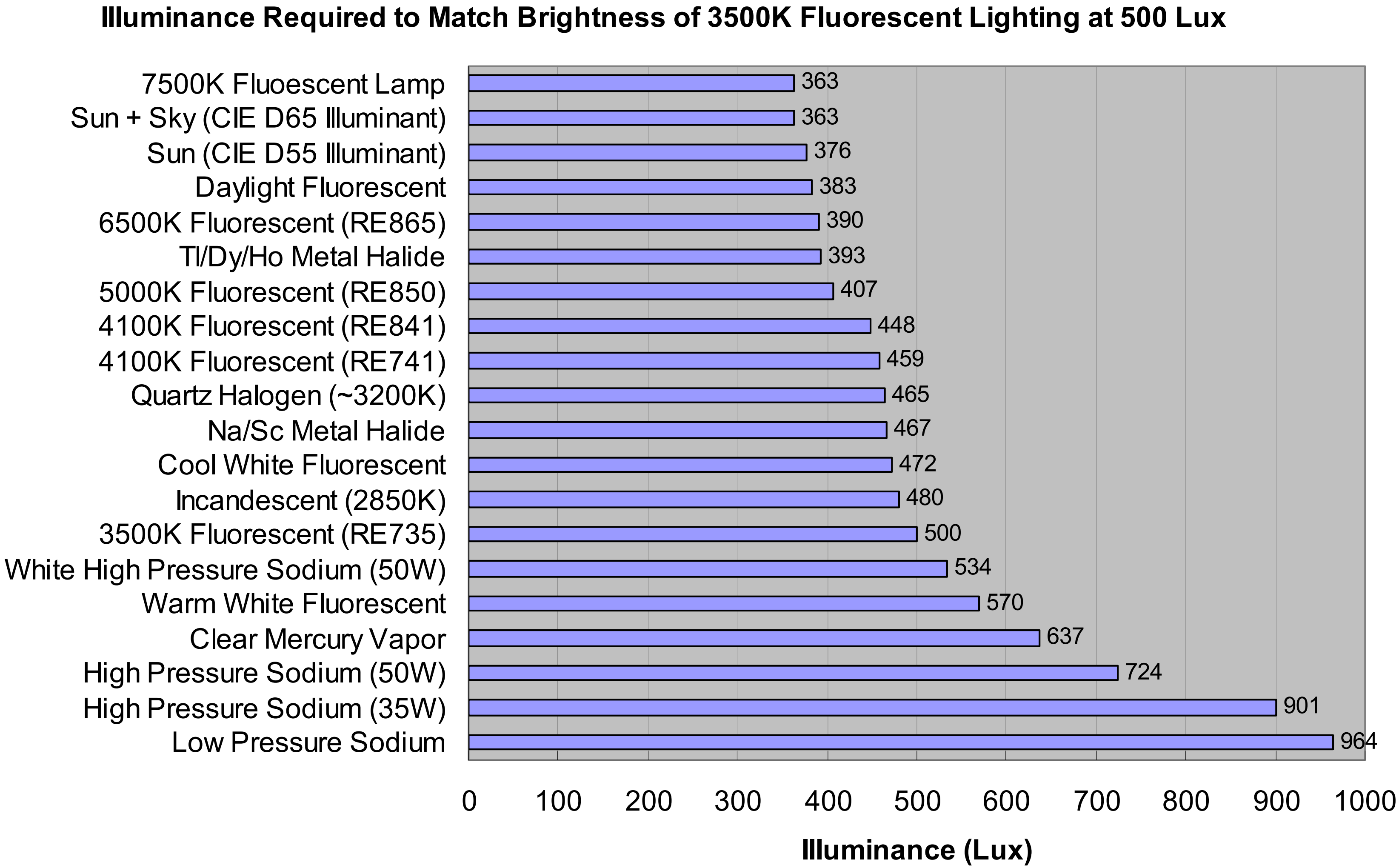
...and OOPS, the Lumen May be Wrong, Too

- **Derivation of the Lumen**
  - Average response of a small population of young, northern European viewers
  - Perceived intensity of a colored light source
  - Viewed through a small incident angle
  - Response is V(λ)
  - Monochromatic green light at 555 nm is 683 Lumens / Watt



- **Established as the fundamental measure of visible light**
- **Data, however, is accumulating that indicates it may not be a good representation of how we see**

...Because Equal Perceived Brightness Does Not Correspond to Equal Lumens



Reference: "Energy Efficiency Consequences of Scotopic Sensitivity," S.M. Berman, Journal of the IES, Vol. 21, No. 1, Dec. 1992.
Berman ,S.M. 2000: The coming revolution in lighting practice. Energy Users News Oct, 25,10 23-25.

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Differences Between the Definition of the Lumen and Lighting Perception

- **Narrow field of view used for Lumen stimulus**
  - Ignores response of rods and peripheral vision
  - Rod response blue-shifted 30 nm from photopic curve
- **Single color illumination used for Lumen stimulus**
  - Analysis of human vision neural processes indicates
    - Coordinated processing of rod/cone stimuli
    - Differential balancing of stimuli
    - Embedded coding of information beyond the local stimulus
  - Perceived (neural) brightness of a colored light source may not be indicative of perceived brightness of white light
- **Population of test subjects needs to be broadened with respect to age, race, culture.**

Why the History Lesson?

- **Don't make the same mistakes**
- **Don't presume that conventional lighting technology is standing still**
- **Full disclosure**
  - Definitional shortfalls
    - CRI
    - Lumen
  - Industry-internalized "optimizations" that game these

…set you up to "shoot ahead of the duck"

READY

- **Emphasize development of SSL characteristics**
  - Overwhelming advantage in key cost & performance metrics
  - Target specific “vulnerable” market segments
- **SSL will NOT be dominant technology by 2010**
- **SSL might**
  - Dominate targeted market segments by 2010
  - Dominate broader lighting market by 2030
- **Align development priorities to schedule of targeted markets and relevant cost & performance metrics**

Near Term Opportunities

- Track and recessed lighting
- Automotive lighting
- Digital projectors

Track and Recessed Lighting

- Currently served by PAR38, PAR30, PAR20, R-30, and MR-16 families of lamps
  - Beam-formed outputs
- PAR- and R-lamps
  - Price: $5-10 / kilolumen
  - Efficacy: 15 LPW max
  - Output: 250 – 2000 L
  - Edison base
- MR-16
  - Price:
  - Efficacy:
  - Output:
  - Two-pin base
  - Cost of ballast:

KEY METRICS

Performance

- **Color**
  - CRI > 90 (10%Dxx)
  - CCT 3000-5000K
- **Indoor / Outdoor robustness**

Cost

- **Recessed**
  - Socket compatible
  - First cost ~ $10
- **Track**
  - Ballast/lamp replacement
  - First cost ~$25
- **Lifetime > 10,000 hours**

Track and Recessed Lighting Key Challenges

- **Color**
  - × LED + 1 phosphor insufficient
  - × LED + multi-phosphor inefficient
  - ✓ Multi-color Multi-LED multi-chip module
- **Fixture integrated thermal management**
  - Current fixtures assume radiated waste heat
  - SSL generates 5-10X conducted waste heat
    - Increase efficiency to reduce waste heat
    - Integrated thermal management designs
      - Fixture add-on kits
      - SSL lamp features
- **Edison base solid state voltage converter**
  - Cost included in price target
  - Contributes to effective lamp efficiency

Automotive Lighting

- Already a major market for LEDs
  - Indicator lights
  - Running lights
  - Turn & brake signals
  - Dashboard illuminators
- Growing opportunities
  - Small viewing lamps (overhead, trunk, in-door)
  - Headlamps
    - Specialty incandescent std.
    - Xenon-MH premium std.
  - Remote source lighting
    - Headlamps
    - Other “white” lighting

KEY METRICS

Performance

- **Optical Extent**
- **Turn-on time**
- **Re-strike time**
- **Environmental robustness**

Cost

- **Efficiency**
- **First Cost**
- **Lifetime**
- **Total cost of use (inclusive of dmg and replacement cost)**

Autmotive Lighting Key Challenges

- **Efficiency**
  - Includes power converter burden
  - Includes optical transfer burden (e.g. optical extent)
- **Optical extent**
  - Enabling smaller, lower cost headlamp fixtures
  - Enabling remote source lighting distribution
- **Driver electronics**
  - Extreme environmental requirements
  - Included in cost target
- **Cost**
  - Commoditized supply chain
  - 4-6 year design in cycle

Digital Projectors

- **Current systems**
  - LCD
  - DLP (potential LED mkt)
- **DLP projectors**
  - 1-panel light modulator
  - Time sequential color
    - R-G-B-White color wheel
    - Discards >50% of light
  - 100-200 W UHP lamp
    - 60 LPW efficacy
    - >200 Cd/mm^2-sr brightness
    - 1000-6000 hr ANSI lifetime
    - $250-500 consumer cost
    - $100-200 supply cost (est.)

Target LED/DLP Projector

- **1500 Lumens on screen ⇒ 3000 Lumens on DLP**
- **0.7" diag DLP = 15 mm^2-sr**
- **3 LEDs & optical combiner**
  - 12 W optical output (=3000L / ~250L/W_{vis})
  - ~5-4-3 split for B-G-R
  - 30-50% max duty cycle
- **Eliminate**
  - Color wheel
  - Replaceable lamp design
  - Size & weight
- **Color optimizations galore**

Digital Projectors
Key Challenges

- **SMPTE color gamut**
  - ✓ Blue: 430-450 nm
  - o Green: 540-570 nm
  - ✓ Red: 600-630 nm
- **3000L with 200 Cd/mm^2-sr brightness**
  - R-G-B optical combiner (many high efficiency architectures)
  - 10-15 W peak, 3-5 W average light output from ~4 mm^2 lambertian-equivalent
  - Minimize delivered optical extent (near-device optics)
- **$100 price inclusive of power supply**

Key Technology Steps

- **Cost**
  - White light (D65 or RGB)
  - $10 / kilolumen entry point
- **Fixture integrability**
  - "Socket" dependent
  - Integrated thermal design (no fans)
- **High efficiency direct emission deep green LED**
  - 75 LPW white
    - 30% efficient direct deep green
    - 60% efficient blue + 70% efficient phosphor
  - 150 LPW white
    - 60% efficient direct deep green
    - 90% efficient blue + 90% efficient phosphor

Key Technology Steps

- **Basic device efficiency**
  - Lowers cost
  - Leverages fixture integrability
  - Progress to date impressive
    - 2nd gen designs incorporating higher order structures
    - 3rd gen designs to include 3-D fab of active region?
- **Near-device integrated optics**
  - Leverage inherent advantage of SSL
  - Allow optical elements as close as possible to emission
    - Redesign dome/packaging as an optical element?
  - Future opportunity for trans-device integration
    - Device embedded/integrated passive optical elements
    - Design of active region for optimized emission characteristics

Summary

- **Solid state lighting a significant opportunity**
- **Performance already sufficient to target market introductions within next five years**
  - Success will drive pace & depth of eventual impact
  - Failure will tighten available $$ and prejudice market
  - Lack of success = failure (loss of momentum)
- **Development & engineering of near-term market entry products is most critical activity**
  - Integrated-product-team culture (not device-centric)
    - Fixture integration thermal design
    - “Socket compatible” power supplies
    - Multi-chip module integrated lamp systems with controllers
  - Continue to push SSL device R&D, but segregate efforts
- **It’s about “good enough” to “get going”**